Culvert Sizing Techniques

North Coast Redwoods District

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"While we cannot completely avoid watercourse crossing failures, we can reduce failure potential through careful crossing design that accommodates water, wood, and sediment and that reduces potential erosional consequences if and when they do fail" (Cafferata et. al., 2004). Road-stream crossings with undersized culverts can cause large inputs of sediment to streams if the culvert inlet is plugged and streamflow overtops the road fill (Furniss et. Al. 1998). Best et al. (1995) reported that "fill-failures and diversions of road-stream crossings have been found to cause 80 percent of fluvial hillslope erosion in some northern California watersheds."

An on-site evaluation is performed to determine if a culvert is required at the crossing. In some cases, other alternatives such as hardened seasonal fords, rock armored crossings, or drain swales may be appropriate. These alternatives are preferable to a culvert due to their low maintenance and because they can be constructed without introducing fill into the stream channel. Crossing site characteristics such as stream channel depth, stream flow velocities, channel stability, channel gradient, stream bank steepness (stream bank slope grades) stream bank slope stability and approaching road grades into the crossing site all influence the appropriateness of these crossing designs.

The culvert should be sized to convey a discharge equal to or in excess of a 100-year flow event. In addition, determination of the design flow should also include an assessment of the stream's morphology and potential debris accumulation. The culvert should ideally be sized to transport not only water, but the other materials that are mobilized during a flood. California State Parks uses the largest estimated culvert size from 2 office based estimates and the "3x Bankfull Method".

Several office based techniques exist for estimating the 100-year flood flow including the rational method, the USGS Magnitude and Frequency Method, and the flow transference methods (Chow 1964, Dunne & Leopold 1978, CDF 1983, Weaver & Hagans 1994, Waananen & Crippen 1977, and Skaugset & Pyles 1991). However, according to research conducted by Furniss et. al. (1998), hydraulic models are not a reliable predictor of the culvert size needed to pass the 100-year flood because most culvert failures occur from accumulations of debris and sediment at the inlet. Currently, few specific engineering techniques exist for sizing culverts to pass debris and sediment, other than the intuition of experienced designers. In addition, little research has been conducted on appropriate design criteria to allow the passage of organic debris and sediment through culverts. Therefore, for maximum protection of the resources, a detailed assessment of individual crossings is recommended to determine stream channel characteristics that can be used to adequately size culverts and reduce plugging potential.

Several field techniques exist for determining culvert diameter, however these remain relatively untested. The "3 X Bankfull Stage Method" is one technique that has been evaluated by researchers, and appears to be well suited for streams in the Pacific

Northwest. Cafferata et. al. (2004) reported that "the 3 X bankfull stage method is a potential field check that appears to be valid for the coastal portions of northwestern California, but may underestimate Q100 culvert sizes for inland areas away from the rain-dominated portion of the Coast Range." The Forest Practices Code of British Columbia (BC MOF 2002) suggestes this method as a field check to be used in combination with several other methodologies. This method is designed to pass flood flows, and associated woody debris and bedload materials.

To determine culvert size using the "3x Bankfull Method", the bankfull cross sectional area is measured in a stream reach that is not influenced by a road. Before using any field techniques for culvert sizing, road designers should become familiar with channel characteristics described in Applied River Morphology by Dave Rosgen (1996). According to Rosgen, bankfull stage occurs when the stream flow fills a channel to the top of the banks and begins to pour over into the floodplain. To obtain the area of the bankfull channel (Abf), measurements should be taken on the width at the upper bank (W1), the channel width(W2), and the total depth (D). Next, the bankfull cross-sectional area of the stream can be calculated using the equation Abf = (W1 + W2)/2 x D. Because most culverts are considered to be "inlet controlled", the only factor that needs to be considered about the pipe size is the area of the inlet. Therefore, to calculate the appropriate culvert size (Ac), use the equation Ac = 3(Abf). Using an alternative notation where Ac = πr2 (r = radius of the culvert opening), the diameter (d = 2r) of the culvert opening can be calculated as follows:

$$\pi r^2 = 3(\text{Abf})$$

$$r^2 \approx \text{Abf} \text{ (note that this is approximate)}$$

$$r \approx (\text{Abf})^{1/2}$$

$$\text{Therefore, } d \approx 2[(\text{Abf})^{1/2}]$$

The second field technique for determining culvert size is to use the "2 x Area of Highest Flood Indicator" method used by Beers, et. al. (2005). This method is more conservative than the "3x Bankfull Method" because it usually results in a larger culvert size prescription. This method is used to design crossings to pass flood flows as well as associated woody debris and bedload materials. To use this method, the area of the largest recognizable past flood event is determined. Indicators of the magnitude of past flood events include debris captured in stream side vegetation, a silt line on tree trunks, scour line on upper stream bank, and fluvial deposits in the floodplain or on a terrace. Using these indicators, estimate the most probable elevation of the maximum flood event and measure that cross-sectional area using the equation Amf = (W1 + W2)/2 x D. To calculate the appropriate culvert size (Ac), use the equation Ac = 2(Amf). Using an alternative notation where Ac = πr2 (r = radius of the culvert opening), the diameter (d = 2r) of the culvert opening can be calculated as follows:

$$\pi r^2 = 2(\text{Amf})$$

$$r^2 \approx 2(\text{Amf})/\pi$$

$r \approx [2(Amf)/\pi^{1/2}$

Therefore, $d \approx 2[(2(Amf)/\pi.^{1/2}]$

The main cause of culvert failure in forested watersheds is due to accumulations of small twigs, sticks, and branches and not due to large logs (Cafferata, et al. 2004). In general, most of the wood that blocks the culvert inlet is not much larger than the culvert diameter and smaller than the width of the active channel. Most woody material that is longer than the channel width becomes caught in the stream system and is not easily mobilized for more than a short distance. Therefore, by sizing culverts to the physical characteristics of the stream, they will not only be passable to the 100-year storm event, but to any mobilized woody material as well.

In addition to locating and measuring the highest flood indicator, the stream reach above the crossing site must also be evaluated to determine the amount of aggregate and woody debris that could be mobilized in a high flow event. If it is determined that a significant amount of aggregate and woody debris is located above the crossing site that could be mobilized in a high flow event, then the culvert diameter should be increased a minimum of one full size. Example: from a three foot diameter pipe to a four foot diameter pipe.

When sizing culverts, the minimum size pipe that should be used when evidence of a defined channel exists is 18-inches (Crowley, 2003). To evaluate a stream crossing for potential reengineering, the designer should consider the worst case scenario that could occur at the site (Baker et. al. 2001).

Flared end sections increase inlet controlled culvert capacity and help prevent blockage of the inlet by rocks and woody debris (Cafferata, et al. 2004). However, flared inlets have a fixed opening design that often does not conform to the stream's channel characteristics. Culvert headwalls constructed of burlap bags filled with concrete (Quick Crete) and reinforced with steel rebar can be used to shape the culvert inlet so that it conforms to the stream's morphology. These headwalls extend to the full width of the flood channel and to the height of the road bed. Constructing headwalls in this fashion improves the efficiency of the culvert to transport water, aggregate and woody debris by funneling the water flow into the mouth of the culvert. It also helps protect the fill around the culvert inlet from scour and erosion. Any conditions that cause ponding at the culvert inlet increase the potential for culvert blockage by woody material (Cafferata, et al. 2004). Ideally, the stream should flow straight into the culvert inlet at all stream discharges without any eddying or abrupt changes in flow path. If the flow path changes direction, such as the rotation caused by ponding, woody material can become oriented perpendicular to the culvert and increase the chance of plugging.

Furniss at. al. (1998) reported on several other techniques that should be used to increase the capacity of culverts. To be sure a culvert can pass floating wood, the headwater depth to pipe diameter ratio (HW/D) should be significantly less that 1.0. For example a culvert with a HW/D ratio of 0.5 would be flowing half full during the maximum flow. In addition, culverts should be at least as wide as the stream active channel width. And during installation, every effort should be made to install the culvert at the same gradient as the stream channel and in the same direction as the active channel. Culverts not installed on gradient often result in either scouring or down cutting at the inlet or head cutting at the outlet. They also can result in a deposition of aggregate at the inlet or outlet. Culverts not installed in line with the stream channel often require the water to turn in order to enter the culvert inlet. This condition results in a loss in water, aggregate and woody debris transport efficiency and the scour and erosion of the stream bank and road fill. Culverts should also be installed so that culvert pipe exits beyond the road fill. Culverts exiting into the fill or onto the fill will erode the fill material and destabilize the road prism.

When replacing a culvert and the stream gradient is too steep or the stream valley is too deep to install the culvert on stream grade, then it may be necessary to install the culvert with a down drain anchor assembly. Crossing sites with these characteristics should be avoided when designing and laying out roads. Unfortunately, many roads exist where these conditions are present. To keep the culvert from draining onto the road fill a connector fitting of the appropriate angle is attached to the culvert pipe as it exits the fill. Additional lengths of culvert pipe are attached to the connector until the culvert pipe extends below or beyond the fill. This down drain pipe must be anchored to the fillslope to prevent it from separating and diverting water onto the fill. These anchor assemblies must be manufactured for this purpose. Post, pipe and an assortment of wire, straps or rope are not appropriate anchors for this type of design. When using down drain anchor assemblies, it is important to only use galvanized steel culvert pipe as plastic pipe will deteriorate when exposed to ultra violet light.

When installing a culvert, the approaching road grades should be higher than the finished road grade above the culvert. Where culverts are installed at stream crossings the road alignment should pull up and into the crossing while gradually dipping down. It should then gradually pull up out of the crossing. This “critical” dip design keeps the road alignment on contour and results in the stream crossing site being lower than the either of the approaching road grades. If the culvert were to fail, the water would pass over the road and re-enter the stream channel below the road prism and not be allowed to either be diverted down the road or onto adjacent slopes. Pulling into the crossing site in this manor will also result in the need for less road fill material at the crossing site, therefore significantly reducing the road fill material lost in the advent of a culvert failure.

To prevent culvert plugging, one large culvert is more effective than several smaller ones (Furniss, et. al. 1991). However, if conditions exist which do not allow the deeper fill needed to cover a larger pipe, or if the stream is braded and spread out over a large flat area, several medium sized pipes can be used. When using multiple pipes, they should be separated by at least one culvert diameter apart (Crowley, 2003). This separation allows for the proper compaction of the soil material placed as backfill around the pipes. Properly compacted backfill is critical in preventing “piping” of water around the culverts which will eventually lead to crossing failure.

The use of “trash racks” to prevent materials from entering culvert inlets is not recommended except under special circumstances. Trash racks require continuous maintenance to be affective, and only trash racks designed to be cleaned using typical equipment such as a backhoe or an excavator should be used. The problem with trash racks is that they can become buried and plugged with material during a single large storm event and do not allow for natural fluvial transport processes to occur. Once they become plugged the stream will move laterally and scour away the banks adjacent to the trash rack. This could cause severe bank erosion and lead to the failure of the culvert.

In locations where large volumes of fill will be incorporated into the crossing design and the consequences of culvert failure are greater, additional 6-inches of diameter should be added for every 5-feet of fill above the outlet (Spittler pers. com reported by Cafferata, et al. 2004). This means, for example, that a culvert sized at 36-inches that will have 10 feet of fill used to construct the travelway would need to be increased to a 48-inch pipe. This increase helps to reduce the potential cost of importing large volumes of fill to repair the site if failure occurs.

More desirable to increasing the culvert size is to build stream crossings with the minimum amount of fill necessary to protect the pipe and provide access. The rule of thumb for fill depth above a culvert is 12-inches or half of the culvert diameter, whichever is greater (Wiest, 1998).

Refrences

Association (1996) *Aerial Landslide Survey Of Mapleton Ranger District Following Rainstorm Of February, 1996*. Association Of Forest Service Employees For Environmental Ethics.
http://www.efn.org/~jpreed/landsl.html

Baker, Dan; Cahoon, Joel; & Jodi Carson (2001). *Rating system for rural culvert crossing repair and maintenance*. Civil Engineering Department, Montana State University. Bozeman, MT.
http://www.coe.montana.edu/wti/wti/display.php?id=11
http://www.coe.montana.edu/wti/Projects/culvert.htm
This report describes the use of an excel template that was developed to calculate a condition index for culverts. The condition index is a value assigned to each culvert that can be used to prioritize relative maintenance and replacement needs. The template was developed from a statistical analysis of data collected by the Montana Department of Transportation.

BC MOF, (2002). *Forest road engineering guidebook*. Forest Practices. Br., British Columbia Ministry of Forests., Victoria, B.C. Forest Practices Code of British Columbia Guidebook. 208 p.
http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/guidetoc.htm
http://www.for.gov.bc.ca/tasb/legsregs/fpc/FPCGUIDE/Road/FRE.pdf
The Forest Road Engineering guidebook is "intended primarily for skilled, experienced, and knowledgeable technical personnel who are responsible for locating, designing, building, maintaining, and deactivating forest roads"(1). The information provided in the guidebook is intended for use by experienced road engineering practitioners to help them interpret and meet the requirements of the Forest Practices Code of British Columbia

Act, and associated regulations. The guidebook includes a strong emphasis on safety protocol and operational procedures, as well as an emphasis on protecting the natural resources from direct impacts of construction and from long term impacts related to erosion and sediment delivery to streams. The guidebook begins with a section on road layout and design that describes route selection and layout, field investigation, surveying, and associated engineering practices to provide site-specific road location, design, and construction specifications. The next section, design and construction of bridges and stream culvert, outlines the general design requirements for bridges and stream culverts, and discusses non-professional and professional design responsibility, site and site survey information requirements for bridges and major culverts, preparation of construction drawings, specifications for bridges, major culverts, and stream culverts, and methods to estimate design flow discharge for streams. Following the sections on layout and design, the manual moves into road construction with information to assist technical personnel in constructing roads appropriate for the expected service life while minimizing any adverse impacts on other forest resources. Next, the manual covers road drainage construction, which covers drainage system construction, the purpose of which is to maintain natural surface drainage patterns while intercepting, collecting, and controlling flows to minimize any adverse impacts to the environment. The next section, road and structure inspection and maintenance, provides information to assist those responsible for the inspection and maintenance of roads and associated structures. And finally, the last section outlines road deactivation and describes the objectives, levels, and techniques of forest road deactivation.

Beers, Don (1995) *Personal Communication*

Best, D. W., H. M. Kelsey, D.K. Hagans, and M. Alpert. 1995. "Role of Fluvial Hillslope Erosion and Road Construction in the Sediment Budget of Garret Creek, Humboldt County, California." P. M1-M9 In: Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. K. M. Nolan, H. M. Kelsey, and DC: Marron, eds. U.S. Geological Survey Professional Paper.
http://www.krisweb.com/biblio/redwood_usgs_bestetal_1995_1454m.pdf
The purpose of this report was to describe the processes and magnatitude of hillslope erosion in a subwatershed of Redwood Creek, California. The report describes the Garrett Creek Subwatershed and a method used to identify sediment sources and storage mechanisms. The report examines fluvial hillslope erosion, stream crossing diversions, and crossing failures that contributed sediment to Redwood Creek.

Burroughs, Edward, & John King (1989). *Reduction of soil erosion on forest roads*. General Technical Report INT-264. USDA Forest Service, Intermountain Research Station. Ogden, Utah.
This paper provides land managers with a summary of the effectiveness of

various road treatments and practices used to reduce road surface erosion and sediment transport to streams. The paper includes a literature review on numerous mitigation measures used to reduce erosion of the travelway, fillslopes, cultslopes, and roadside ditches, and includes the results of research conducted to measure sediment loss using natural rainfall and rain simulated plots.

Cafferata, Peter; Spittler, Thomas; Wopat, Michael; Bundros, Greg; & Sam Flanagan (2004). *Designing Watercourse Crossings for Passage of 100 Year Flood Flows, Wood, and Sediment*. California Department of Forestry and Fire Protection. Sacramento, CA. http://www.fire.ca.gov/ResourceManagement/PDF/100yr32links.pdf
The Designing Watercourse Crossings document describes three traditional office based techniques for estimating the 100-year recurrence interval water discharge to be used for sizing stream-crossing culverts, and one field based technique for evaluating proposed crossing diameters based on channel characteristics. The report describes the use of the rational method, the USGS magnitude and Frequency method, and flow transference methods; and the 3 times bankfull stage method, and includes suggestions for improving the methods based on the experience of numerous professionals working in the field. The report describes typical problems related to stream crossing failures, and provides a background for the need to improve crossing design. The report includes a discussion of issues related to wood and sediment passage at crossings, and describes techniques used to prevent stream-crossing failure on non-fish bearing streams.

California Department of Fish and Game (2004) *California Salmonid Stream Habitat Restoration Manual*. CDFG Inland Fisheries Division, 1416 Ninth Street, Sacramento, CA 95814 or call (916) 654-5997.
The California Salmonid Stream Habitat Restoration Manual was expanded in 2004 to include Part X, Upslope Assessment and Restoration Practices, which is the DFG standardized protocol for implementation of upslope restoration projects including road reengineering. The manual primarily describes an in-depth approach to assessing upslope erosion to prioritize sites for watershed restoration work. The manual also includes construction guidelines for road decommissioning and road reengineering. The guide includes a discussion on road upgrading and examples of costs associated with the different upgrading tasks. The guidebook includes numerous graphics displaying information on stream crossing upgrades and road surface drainage improvements. The methods described in this manual are aimed primarily at “implementation of cost-effective erosion control treatments in Salmonid watersheds,” with a goal of reducing “the human influences and restore erosion to a level more consistent with the natural background rate.”

CDF (California Department of Forestry and Fire Protection). 2003. California Forest Practice Rules 2003 prepared for California Licensed Timber

Operators and California Registered Professional Foresters. Sacramento, CA. http://www.fire.ca.gov/ResourceManagement/pdf/FPR200301.pdf
This is a .pdf document of Title 14, California Code of Regulations Chapters 4, 4.5 and 10 that was prepared for California Licensed Timber Operators and California Registered Professional Foresters.

Chow, V.T. (1964). Handbook of applied hydrology. McGraw-Hill Book Company, New York. p. 20-8.

Copstead, Ronald (1997). *The Water/Road Interaction Technology Series*. USDA Forest Service, San Dimas Technology and Development Center. San Dimas, California. http://fsweb.sdtdc.wo.fs.fed.us/programs/eng/w-r/w-r.html
The technology series is a set of technical papers describing hydrology issues important to develop, operate, and manage forest roads. The technical papers were prepared to communicate information about road and water interactions to field personnel, to identify knowledge gaps, and to provide reference material for future research. The series was prepared for use by engineers, technicians, physical scientists, fish biologists, and economists working in the field on road construction and maintenance. The series is divided into three main sections including Surface Drainage, Subsurfce Drainage, and Drainage Crossings with each section having numerous detailed papers on the topic. The Surface Drainage section includes the interaction of water with road surface features such as ditches, cross drains, and the travelway surface; with concentration of flow and risk assessment being a critical component. The Subsurface Drainage section documents changes in below ground flow due to the alterations in infiltration, permeability, and intersection of subsurface flow, and how these changes can be measured using field instruments. The Drainage Crossing section describes the selection of materials and the sizing of crossing structures to allow for passage of storm flows, bedload, debris, fish, and other aquatic species. And in conclusion, the series provides an annotated bibliography with over 400 articles, publications, and documents related to the road and water interaction.

Crowley, Christopher, (2003). Ten *rules of thumb for culvert crossings*. Erosion Control Magazine, September/October. http://www.forester.net/ecm_0309_ten.html.
This article provides 10-rules-of-thumb that can be used in the design and construction of culvert stream crossings based on the authors extensive observations of culverts. The article includes discussion of issues related to snow melt and covers many common problems related to culvert installation. The article includes technical advice and engineering standards, however is written in a style that is understandable to a wide range of audiences.

Dunne, T. and L.B. Leopold. (1978). Water in environmental planning. W.H. Freeman and Company. San Francisco, CA. 818 p.

This book is still the best comprehensive introductory hydrology book in existence. provides a good balance among applied context, quantitative tools, and conceptual descriptions of basic and integrated processes while retaining its comprehensive character without copious mistakes and errors. great tool of reference for the planner of any type. It addresses key issues in the role of water during the planning process and also includes important formulas for solving water problems. A well-written general book on hydrology with an emphasis on applied problem-solving. Although some sections are dated, much of the material in this book is still relevant.

Foltz, Randy (2003). *Environmental impacts of forest roads: an overview of the state of the knowledge*. USDA Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory. Moscow, Idaho.
This report reviews literature on the environmental impacts of forest roads at the on-site and watershed level with a focus on erosion of the road prism. The report describes the research that has been conducted on the influences of traffic on road generated sediment and describes some mitigation techniques to reduce traffic related impacts. The report also summarizes studies looking at changes in hydrologic response due to roads.

Furniss, M.J., T.S. Ledwith, M.A. Love, B. McFadin, S.A. Flanagan. (1998). Response of roadstream crossings to large flood events in Washington, Oregon, and Northern California. USDA Forest Service. Technology and Development Program. 9877--1806—SDTDC. 14 p.
http://www.stream.fs.fed.us/water-road/w-r-pdf/floodeffects.pdf
Part of the Water / Road interaction series, this report describes an inventory of failed road stream crossings on public lands in areas of the Coastal, Cascade, Klamath, and Blue Mountain Provinces of the Pacific Northwest. The objectives of the survey were to identify the mechanisms and on-site consequences of road-stream crossing failures and to evaluate a potential watershed-scale screening method for its use in predicting road failures. The report describes the mechanisms of road crossing failure and a discussion of potential techniques to minimize crossing failure.

Harr et al., (1996) *Changes in Storm Hydrographs*; J. A. Jones and G. E. Grant, *Peak Flow Responses to Clear-Cutting and Roads in Small and Large Basins, Western Cascades, Oregon*, *Water Resources Research* 32: 959-974

Harr, R. Dennis and Roger A. Nichols (1993). *Stabilizing forest roads to help restore fish habitats: a northwest Washington example.* Fisheries 18(4):18-22.

Keller, Gordon, & James Sherar (2004). *Low volume roads engineering: best management practices*. Washington DC: US Agency for International Development and USDA Forest Service International Programs.
http://zietlow.com/manual/gk1/web.doc

The *Low volume roads engineering: best management practices* guide is a field manual “intended to provide an overview of the key planning, location, design, construction, and maintenance aspects of roads that can cause adverse environmental impacts and to list key ways to prevent those impacts.”(p. 7) The guide describes the use of Best Management Practices to reduce pollution and maintain water quality; and includes a brief discussion of road decommissioning and road closure. The guide was written to “address most basic roads issues in as simple a manner as possible”, and recommends that more complex issues be handled by an experienced engineer. The guide includes a list of “do’s” and “don’ts” which are recommended practices, and practices to avoid. The guide begins with an introduction to low volume road engineering and a method for conducting an environmental analysis. The guide then covers key planning issues such as reducing vulnerability of roads to natural disasters, streamside management zones, and timber harvesting. Next the guide moves into the actual engineering of low-volume roads, and includes chapters on drainage crossing design, hydraulics, road drainage, culverts, fords, bridges, slope stabilization, roadway materials, erosion control and stabilization of gullies.

Kramer, Brian (2001). *Forest Road Contracting, Construction, and Maintenance for Small Forest Woodland Owners*. Oregon State University, College of Forestry, Forest Research Laboratory.

The Oregon State University handbook is a guide to building and maintaining cost-effective, environmentally sound logging roads on non-industrial timber lands within the state of Oregon and Washington. The text is written in a nontechnical format so it can be more available to landowners who have little experience with road engineering. The handbook describes construction techniques for all-season and dry-season roads.

Ministry of Forests, (2002). *Forest Service Bridge Design and Construction Manual*. British Columbia Ministry of Forests, Resource Tenures and Engineering Branch.

The Bridge manual provides the minimum expected administrative processes and specifications for the design, fabrication, and construction of Ministry of Forests bridges. This manual provides detailed design standards for the various bridge components along with expected fabrication and inspection details. The manual begins with a general discussion of the documentation and procedures of bridge construction. Next, the document covers generic design standards and then fills the gaps with information on detailed design standards. The manual contains a section on materials including steel, concrete, and wood products, and includes new and innovative uses of these materials. The manual also describes fabrication techniques, transportation issues, and construction specifications.

Rosgen, Dave, Rosgen, D. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, Colorado. p. 2-2. Available at http://www.wildlandhydrology.com/html/applied.htm

Skaugset, A.E. and M.R. Pyles. 1991. Peak flow estimation and streamflow simulation for small forested watersheds. Unpublished Report prepared for a workshop titled Design and Maintenance of Forest Road Drainage, 18-20 November 1991, Oregon State University, Corvallis, OR. 19 p.

USDA (2002). *Management Techniques for Riparian Restoration: Road Field Guide*. United States Department of Agriculture Forest Service, Rocky Mountain Research Station. Fort Collins, Colorado.
The Road Field Guide is a pocket-sized booklet containing information on various management techniques for management of roads located adjacent to riparian areas. The booklet includes 1 to 2 page descriptions of the main issues related to road construction, reengineering, and maintenance. The booklet includes full color photographs and graphics that illustrate important aspects of various road structures or construction techniques. Each topic is broken down into first a description of the issue, the application of the structure, important considerations, potential benefits, and potential alternatives or complementary techniques. The booklet includes retaining walls, slope rounding and revegetation, revegetation, soil bioengineering, invasive species, biotechnical stabilization, landslide mitigation strategies, ditch treatments, roadway dips, low water crossings and fords, permeable fill with culvert array, culverts, raised culvert inlets, energy dissipaters and debris racks, bridges, surfacing techniques, mobile rock crushing/rotor trimmer, stream channel modification structures, reconnecting cutoff water bodies, log jam complexes, fish passage, wildlife crossings, beaver pond structures and wetland maintenance.

Waananen, A.O. and J.R. Crippen. 1977. Magnitude and frequency of floods in California. U.S. Geological Survey. Water Resources Investigation 77-21. Menlo Park, CA. 96 p.

Weaver, William (1996). *Post-Storm Aerial Reconnaissance of the Middle Oregon Cascades and Middle Coast Range*. Pacific Watershed Associates Geomorphic Studies. <http://www.efn.org/~jpreed/landsl.html>.

Weaver, William, and Danny Hagans (1994). Handbook for Forest and Ranch Roads. A guide for planning, designing, constructing, reconstructing, maintaining, and closing wildland roads. The Mendocino Resource Conservation District. Copies available from MCRCD, 405 Orchard Ave., Ukiah, CA 95482.
The Handbook for Forest and Ranch Roads is considered by private landowners of California to be the best publication available on the topic of wildland roads. The manual is “aimed at producing efficient, low-cost, low-impact roads that have a minimal effect on the streams of a watershed.” The Handbook is designed to be a field manual and a practical guide that

can be combined with personal experience and good judgment to each "on-the-ground" situation. The Handbook begins with an introduction to watershed science and road related sediment issues; and describes the process of planning and designing low-cost roads. After the introductory chapters, the Handbook describes in detail road layout and the tools helpful in laying out a road in the field. The Handbok then discusses road design, including surface drainage, road prism, and special conditions. Next the Handbook provides detailed information on road drainage structures such as stream crossings, bridges, rolling dips, and ditches. Following the planning sections, the book covers the construction phase from grubbing and clearing to surfacing and erosion control. After the road is in place, maintenance is required on an annual basis, and the Handbook identifies the necessary steps of maintenance operations. Lastly the Handbook covers road abandonment and road closure, which are an important aspect of any road management program.

Wiest, Richard (1998). *A landowners guide to building forest access roads*. United States Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. Radnor, PA. http://www.na.fs.fed.us/spfo/pubs/stewardship/accessroads/accessroads.htm. This guide is oriented toward owners of small private woodlots to provide the basic information needed to avoid the high costs, land disturbance, degradation of water quality, and destruction of fish habitat that can result from poor development, construction, and maintenance of forest roads. This guide applies to temporary and seasonal low-speed forest roads with a narrow running surface. Recommendations in this guide include basic planning criteria, construction specifications, drainage techniques and structures, maintenance, and closure of low-volume forest roads. The guide discusses situations that require special considerations such as streams with or without migratory fish, beaver ponds, and wetlands. The recommendations in this guide incorporate best management practices, which are designed to reduce nonpoint-source pollution.

Wilbrecht, Scott (2000). *Forest Roads Manual*. Oregon Department of Forestry State Roads Program. Salem, OR.
http://www.odf.state.or.us/DIVISIONS/management/state_forests/RoadsMan.asp
http://www.oregon.gov/ODF/STATE_FORESTS/Roads_Manual.shtml
The Forest Roads Manual is a management document designed to provide guidance and standards for road management on state-owned forestlands in Washington. The manual is aimed at forest roads used primarily for forest management, timber removal, recreation, and fire protection. The manual describes the vision for Washington's state owned forest roads and includes a list of guiding principals for road management. The document begins with a section on transportation planning and road inventory to help develop a vision of the transportation network. Following planning, the manual has a section of forest road design and includes information on engineering procedures, design standards, stream crossings, surface drainage and road alignment. The manual also covers

the essentials of road construction from clearing and grubbing to road bench construction to finishing and erosion control treatments. The manual also includes a section on project administration, and provides some tools and advice to contract inspectors. The manual then covers monitoring, evaluation and road maintenance activities, and describes the policy related to use of forest roads for timber operations. Lastly, the manual describes “forest road vacating” which is another term for road obliteration or decommissioning.